On the Annual Cycle in Surface Pressure on the Tibetan Plateau Compared to Its Surroundings

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ABSTRACT

The authors have investigated the climatological annual cycle in surface pressure on the Tibetan Plateau in relation to the annual cycle in surface pressure at the lower surroundings (India and China). It is found that surface pressure on the plateau is low (high) when the surrounding Asian continent has high (low) pressure. This out-of-phase relationship is evident in the NMC analyses and in long runs made with the NMC's global model. The authors have also found a few station observations on the plateau that have partially confirmed these opposing annual cycles in surface pressure. The authors believe this contrast to be real and operative over other parts of the globe as well. Near mean sea level, the surface pressure is low (high) when the temperature is high (low) (relative to its surroundings). At higher elevations, pressure is low (high) when temperatures are low (high). Also, in the datasets studied, the authors found no evidence for a thermal low on top of the plateau in summer.

1. Introduction

We have examined the annual cycle of surface pressure p_* in a 10-yr-mean global model climatology (Van den Dool and Saha 1993, hereafter DS93), produced at the National Meteorological Center (NMC). Defining "anomaly" as the deviation of the 10-yr monthly mean from the annual mean, this model climatology reveals that during northern winter the p_* anomaly is positive over much of Asia but negative over the Tibetan Plateau (see Fig. 1 top). Generally, over much of the planet p_* is high when the lower boundary temperature is low (DS93). By the same empirical rule, much of Asia has a surface pressure deficit in July, but now the plateau has its highest pressure (see Fig. 1 bottom).

This inverse relationship in the mean monthly surface pressure anomaly between low-level Asia and the higher elevations (the Tibetan Plateau is, on an average, 4–5 km above sea level) is equally evident in a 6-yr-mean (1986–1992) January and July climatology of surface pressure based on NMC analyses (Fig. 2). By showing January and July only, we have presented the seasonal extremes of the annual cycle in p_*, which can be characterized by a single harmonic mostly. The approximately 180° phase difference between the lower and the higher elevations disappears after reduction to mean sea level (see Fig. 3 in DS93, or Hsu and Wallace 1976). We therefore emphasize that we use surface pressure throughout this paper.

To our knowledge, the phenomenon of opposing annual cycles in p_* between a plateau and its low surroundings has not been discussed in the literature, even in otherwise exhaustive books on mountain climatology (see, e.g., Barry 1992). Part of the reason may be a lack of observations at enough stations for enough years in high terrain.

Since Tibet and its lower surrounding areas both get cold during January and warm during July, why is the relationship in surface pressure inverse between them? Is it simply due to the difference in altitude or are the characteristics of the atmosphere in mountainous areas so as to force this kind of an inverse relationship? Does the plateau have a heat low in summer, as speculated by Tang and Reiter (1984), to be in place at least during the daytime? Are there any useful analogies to be made with the diurnal cycle and its associated up- and downslope winds? How does this fit in with the observed monsoon circulation over the region as a whole? Are we witnessing a third seasonal reversal of pressure (and wind) patterns, the first two being between the hemispheres and between land and sea (see DS93)?

These questions call for a detailed examination of not only the surface but also the upper-air structure of the atmosphere over the region in different months of the year. This is done in the present study primarily by using available station observations over the region, particularly India and China (representing the lower surroundings) and the Tibetan Plateau, although for the latter it is hard to find plentiful data. We also rely on the NMC analyses, even though we realize that the

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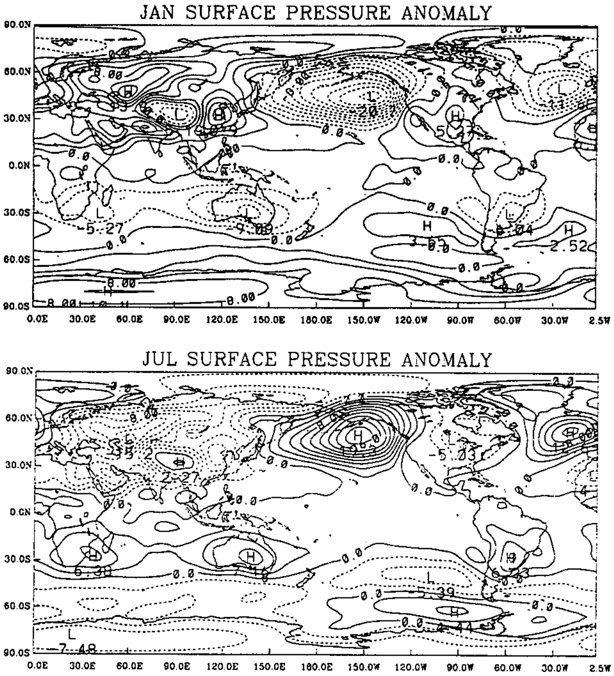

FIG. 1. Surface pressure anomaly (deviation of monthly climatology from annual-mean climatology) in January and July derived from a 10-yr run NMC global model. Units are hPa. Isobar interval 2 hPa. Negative contours dashed.

analyses data are to some extent fabricated in areas where observations are sparse or absent. Because the model (Fig. 1) and analyses (Fig. 2) agree quite well on the phenomenon, the data from the 10-yr run (no missing "observations," perfect dynamical consistency, etc.) should also be useful.

The purpose of this note is to call attention to and describe the phenomenon of opposing annual cycles in surface pressure between a plateau and its surrounding lowlands. In the process we will speculate about its causes.

2. Data

The sources of data are 1) World Meteorological Organization monthly climatic data for the world, 2) the 10-yr-mean NMC global model climatology available from the Climate Analysis Center at NMC (Van den Dool et al. 1991), and 3) the 6-yr-mean (1986–1992) monthly observed climatology over the globe prepared by the NMC through its daily global data assimilation system; however, see the appendix for several caveats.

From the first source we have taken three Indian stations, namely, Port Blair II (11°40′N, 92°43′E; 79 m), Calcutta (22°32′N, 88°20′E; 6 m), and Gauhati (26°06′N, 91°35′E; 54 m); two Tibetan stations, namely, Lhasa (29°40′N, 91°08′E; 3650 m) and Dulan (36°18′N, 98°06′E; 3192 m); and a Chinese station named Urumqi (43°47′N, 87°37′E; 919 m) during a 3-yr period (1986–1988). At the Indian and Chinese stations, our data consist of pressure and temperature at the surface and the geopotential height and temperature at the standard pressure surfaces 700, 500, and 300 hPa. Data over the Tibetan Plateau consist of surface data at both Lhasa and Dulan and geopotential height and temperature at 500 and 300 hPa over Lhasa only, since no upper-air data were available from Dulan. We would have preferred to include stations at elevations higher than Dulan but were unable to locate any. Likewise, for a cross section along 90°E we would have preferred stations on the plateau to the west of Dulan but were unable to find any.

3. Annual cycle of surface anomalies (station data)

The mean monthly anomaly of surface pressure and temperature, computed for different months of the year, is presented in Table 1.

Since surface temperature anomalies are directly related to insolational heating (though with some measure of time lag), the seasonality in the distribution of the anomalies is clearly evident in Table 1. It shows that the minimum temperature is reached at all stations sometime in January or February. The anomalies are generally positive during the summer. However, the times of changeover from negative to positive anomaly as well as attainment of a peak value at the height of summer varies with the location of the station. The changeover appears to occur earlier at the southern

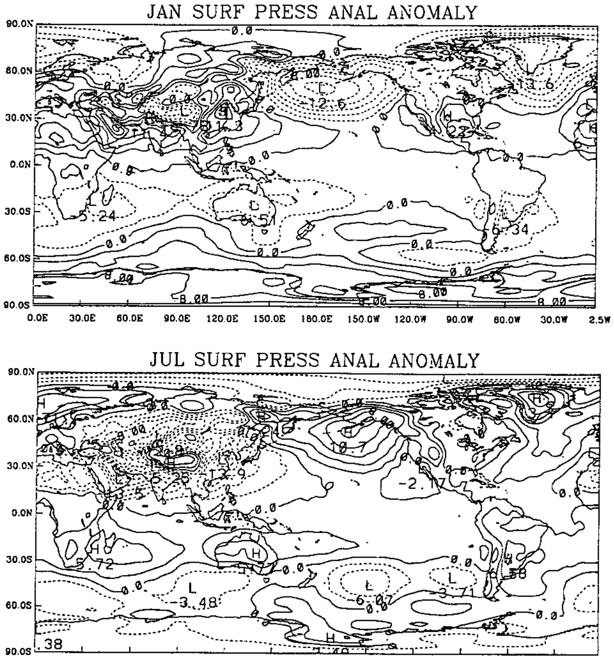

FIG. 2. As in Fig. 1 but now based on the 1986–1992 NMC analyses.

TABLE 1. Mean monthly values of surface pressure anomaly (hPa)/surface temperature anomaly (°C) at Indian, Tibetan, and Chinese stations lying close to the 90°E meridian.

		Indian stations		Tibetan stations		Chinese stations
	Pt. Blair	Calcutta	Gauhati	Lhasa	Dulan	Urumqi
Jan	2.3/−0.7	8.3/−7.2	7.2/−6.8	−1.8/−10.7	−1.2/−11.7	4.0/−16.8
Feb	2.1/−0.7	6.1/−3.7	5.6/−4.7	−1.2/−5.7	−3.1/−8.9	4.0/−17.0
Mar	1.2/0.9	1.6/0.9	0.9/−1.5	−1.9/−3.4	−4.8/−4.7	−2.0/−8.6
Apr	0.2/2.4	−0.9/3.1	−0.7/0.8	−1.0/−0.3	−0.3/0.2	−2.0/3.2
May	−1.7/1.2	−3.6/3.4	−3.3/2.4	−0.9/4.9	0/4.8	−5.0/8.1
Jun	−3.8/0.7	−9.0/3.5	−8.3/4.3	−1.9/9.4	−0.5/9.1	−8.0/12.5
Jul	−1.3/0.1	−8.0/2.1	−7.4/4.1	0.3/8.6	0.7/11.8	−11.0/16.7
Aug	−2.3/−0.4	−6.6/2.5	−6.5/4.1	1.3/6.8	1.3/10.6	−9.0/14.4
Sep	−1.1/−0.3	−2.9/2.0	−2.8/3.3	2.1/5.2	3.8/5.3	−3.0/10.1
Oct	0.4/−0.6	3.0/0.4	1.8/1.2	2.1/−0.2	2.9/−0.2	2.0/−0.4
Nov	0.8/−1.0	3.4/−1.2	5.1/−2.0	3.1/−5.1	1.5/−6.4	4.0/−8.8
Dec	3.0/−1.0	8.7/−5.5	8.0/−4.8	0.7/−8.4	0/−10.2	2.0/−13.9

stations and later at the northern stations. The amplitude of the annual cycle in surface temperature anomaly appears to increase markedly from south to north and is largest at Urumqi.

Table 1 also gives the climatological surface pressure anomaly at the stations for each month. The amplitudes of the annual cycle in surface pressure are much larger over India and China than over Tibet. Their phasing is not quite as strongly opposite as suggested by Figs. 1 and 2. This can be understood perhaps as follows: to the extent that the response to heating is a baroclinic vertical mode, the nodal point turns out to be somewhere near 700 hPa. (This level may also be season and space dependent.) Being only slightly above the node, the annual cycle at the heights of Lhasa and Dulan are small and only weakly representative of the upper air. This will become clear from our analysis of upper-air structure in the next section. In the NMC analyses, the smoothed plateau reaches to almost 500 hPa, solidly in the upper air, and from Fig. 2, one can see +6 (−6) anomalies in July (January) on the plateau. We therefore suggest that station data from levels well above Lhasa and Dulan (if such data were to exist) would show more clearly the opposite phase in the annual cycle in p_*.

4. Upper-air anomalies

A vertical–meridional cross section along 90°E showing the distribution of mean monthly anomalies of isobaric height and temperature at surface and upper-air stations (which lie fairly close to this meridian except Dulan, which has no upper-air data) during January and July is presented in Fig. 3. The salient features of the distribution of the anomalies would appear to be as follows.

a. Temperature anomaly

The largest negative temperature anomalies in January are generally at the surface at all of the stations. They become less negative with height, rapidly at first and slowly later, until above a certain height (which is about 700 hPa over India and China and 500 hPa or even higher over Tibet) the temperature structure becomes more or less isothermal. In July, there is a marked change in the temperature anomaly structure. At the surface, the anomalies are positive everywhere. However, the vertical distribution suggests that over the Tibetan Plateau and most of southern India (south of about 22°N) the positive anomaly at the surface first decreases with height through a thin layer of the overlying atmosphere and then increases through a deep layer of the middle and upper troposphere. The warmest anomaly appears to be located over the Tibetan Plateau at or above 300 hPa. Over India, a "trough" of minimum temperature anomaly (still positive) appears to be near the surface near Calcutta and, from there, slopes equatorward with height reaching about 700 hPa over Port Blair.

b. Height anomaly

The distribution of height anomalies shown in Fig. 3 brings out the meridional and vertical height gradients that are generally consistent with the monsoon circulation over the region. (In this figure, the surface pressure anomalies reported earlier have been converted to height anomalies at the rate of 8 gpm per hPa for India, 9 gpm per hPa over China, and 12 gpm per hPa over Tibetan Plateau.) In January, there is a north–south pressure gradient at the surface over India that will cause northeasterly trade winds to blow from land to sea near the surface. The anomaly gradient, however, changes with height, and above about 850 hPa, the gradient is reversed to south to north (from sea to land).

In July, the surface pressure anomaly gradient is from south to north driving southwesterly trade winds from the Indian Ocean to blow toward a trough of low pressure that lies near Calcutta and slopes equatorward

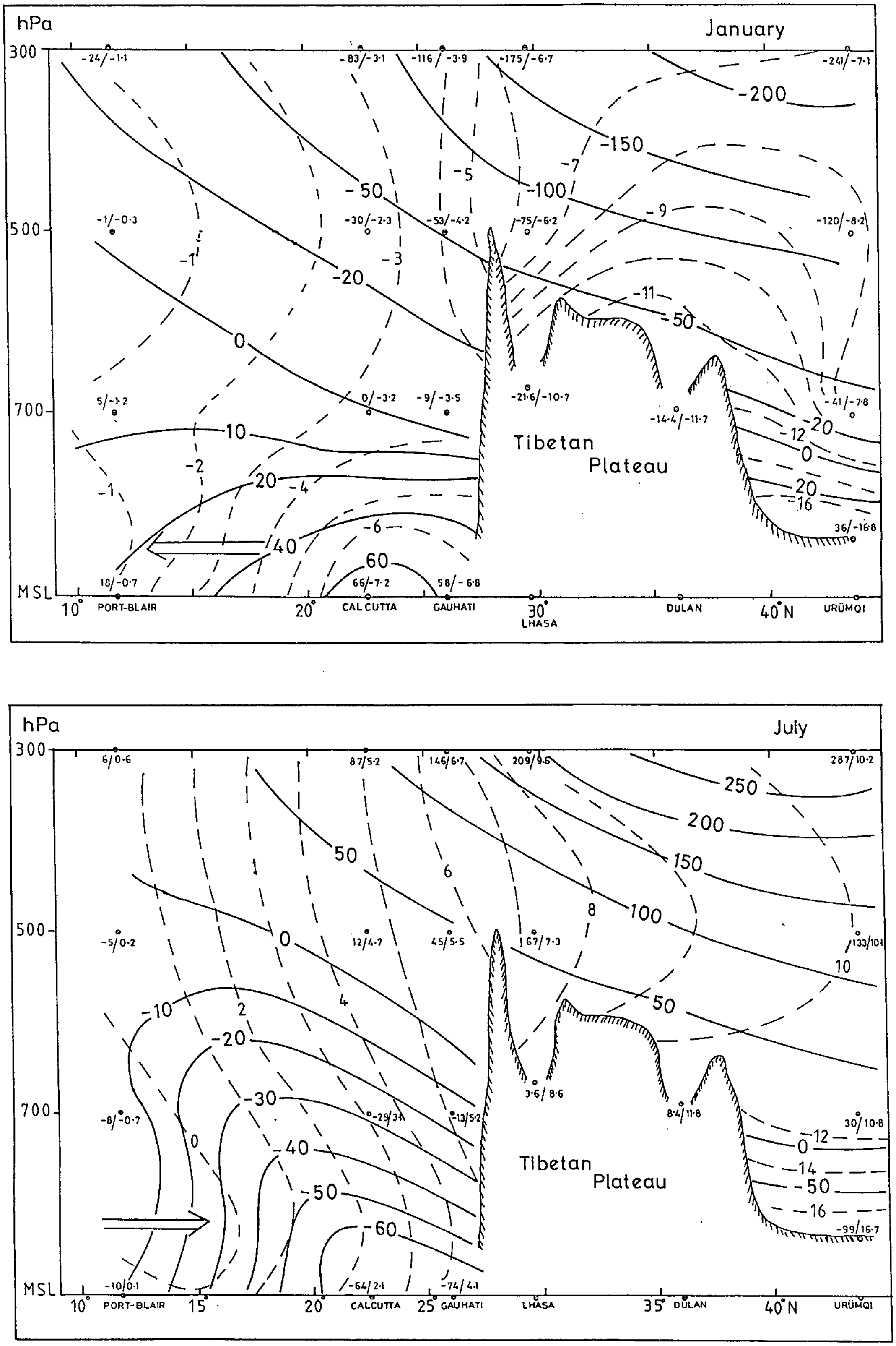

FIG. 3. Meridional-vertical cross section along 90°E of observed temperature (C) anomaly (dashed) and height geopotential meters (gpm) anomaly (continuous) during January and July. Countour interval is 1°C (temperature) and 10 gpm (height).

with height. Higher up, the meridional gradient reverses to north to south. Over the Tibetan Plateau, the pressure (height) anomaly, which is positive already at the surface, increases rapidly with height reaching a maximum in the upper troposphere at or above 300 hPa.

Figure 3 testifies that the inverse relationship in surface pressure anomaly between the Tibetan Plateau and its low-level surroundings during January and July is not an isolated surface phenomenon but part of a larger-scale distribution of anomalies in the atmosphere associated with the mean annual cycle (including the monsoon circulation) over the region.

The observed height anomaly patterns and implied flow patterns presented in Fig. 3 are simulated reasonably well in the 10-yr-mean NMC global model climatology for the months of January and July, respectively. The model cross sections along 90°E are shown in Fig. 4. The orography, represented by a thicker line, differs from reality at T40 resolution. The model has a distinct baroclinic structure with the nodal plane near 700 hPa independent of latitude between 10° and 45°N. Note that the observations (Fig. 3) show a significant slope in its nodal plane. Note also that the model has surface (upper troposphere) anomalies that are too small (large).

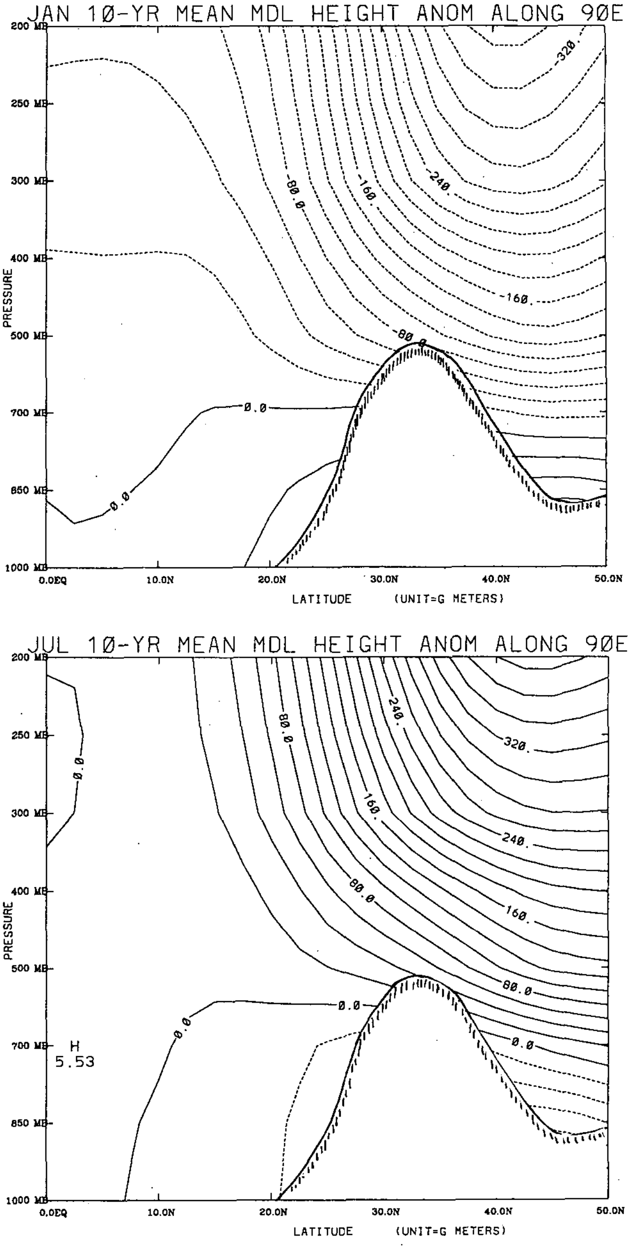

FIG. 4. As in Fig. 3 but now for model-height anomaly. The dashed line here is for the negative anomaly. The thick line is the model's version of the orography. Contour interval is 20 gpm.

5. Conclusions

The present study finds that an inverse relationship in surface pressure anomaly between the Tibetan Plateau and its low-level surroundings during January and July is not an isolated surface phenomenon but part of a larger-scale distribution of temperature and pressure (height) anomalies in the atmosphere associated with the annual cycle in heating and required to drive the observed monsoon circulation over the region.

The most trivial explanation is as follows: the Tibetan Plateau acts primarily as an elevated probe. In other words, Lhasa (at its surface) measures an annual cycle of surface pressure comparable to its own free atmospheric large-scale environment at 650 hPa. In spite of its impressive dimensions, the plateau does not change the annual cycle dictated by the huge Asian continent. If the plateau were much larger, one would expect the lowest (highest) pressure to occur when surface temperatures are highest (lowest). As it is now, the plateau has little or no heat low in the summer, or if it has a heat low, as suggested by Tang and Reiter (1984), it is only shallow and present during the daytime hours. Neither the 10-yr model run nor the NMC analyses show a Tibetan heat low.

At elevations of 3 km or more above the surface, pressure has a minimum (maximum) in winter (summer) at all locations north of 30°N. This is basically because cold (warm) temperatures make pressure decrease fast (slow) with height in winter (summer). The opposing annual cycle in surface pressure is too small to compensate for this temperature effect except at low elevations.

The Tibetan Plateau may be unique in that it is the only large plateau situated on an even larger continent with a very strong annual cycle. This setting allows the inverse relationship to come out rather clearly. There are, of course, other elevated terrains, such as Greenland and Antarctica. These icy lands are like the Tibetan Plateau in that their lowest (highest) surface pressures are reached when the surface temperatures are lowest (highest). The surroundings of both Greenland and Antarctica are ocean, not lower land. Therefore, the pressure anomalies over Greenland and Antarctica at the surface merge with those over the neighboring oceans, being of the same sign.

The latitude of the Tibetan Plateau must also play a role in a full explanation. The response to the July versus January heating anomaly tends to be baroclinic (changes sign in the vertical) in low latitudes. In higher latitudes, the equally impressive seasonal reversal contains a strong barotropic component. (Of course, not just heating but also mountain forcing accounts for this.) The presence of an anomaly in Tibet of one sign from the surface to the tropopause can be interpreted as either the upper half of a baroclinic response or a barotropic response.

A closer examination of Figs. 1 and 2 may reveal several other elevated areas over the globe with an inverse relationship in surface pressure with their surroundings. For instance, notwithstanding the fact that North America is a small continent and the mountains are not as high, the Canadian and United States Rocky Mountains appear to stand out somewhat as an anomaly compared to the surrounding land over North America.

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APPENDIX

"Observed" Surface Pressure Data

We are using a surface pressure climatology based on 6 yr (1986–1991) of NMC analyses. These analyses were produced in conjunction with NMC's global spectral model forecasts. The data assimilation for this model is described elsewhere (NMC 1988). Briefly, each cycle consists of a 6-h forecast to produce a guess field followed by data ingestion at 18 levels over the globe. It is important to understand that the surface pressure data used here are based on much more than observed surface pressure data alone. In fact, in data-sparse areas such as the Tibetan Plateau, the analyses will reflect mostly the data assimilated at earlier times elsewhere—not only surface data but also upper-air wind, temperature, and height data. For the present purpose it is also important to note that because of finite resolution the orography is not perfectly represented. The Tibetan Plateau in model-generated data (including the analyses) may differ significantly from reality.

Another problem associated with resolution is that with every change in resolution [during the 6 yr we went from R40 to T80 (13 August 1987) and then to T126 (on 7 March 1991)], the orography and hence the surface pressure change in an unmeteorological manner. Likewise, the change from silhouette orography to mean orography (at the same time T80 was replaced by T126) had an artificial impact on the surface pressure dataset. We overcame these problems by calculating annual-mean surface pressure on a 2.5° × 2.5° grid (as a function of latitude and longitude) for each of the three periods. Denoting the mean by $p1(x,y)$, $p2(x,y)$, and $p3(x,y)$, we then "reduced" the daily pressure fields to the orographic conditions of the most recent period by

during period 1:

$$p(x, y, t) = p(x, y, t) - p1(x, y) + p3(x, y),$$

during period 2:

$$p(x, y, t) = p(x, y, t) - p2(x, y) + p3(x, y),$$

and no change in period 3. This reduction removes all apparent discontinuities pointwise. This procedure is an improvement, even in areas far away from high mountains. In the middle of the oceans, the difference between $p1$ and $p3$ shows a pattern similar to the Gibbs phenomenon.

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